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Analysis of some methods for reducing residual beam curvatures due to weld shrinkage

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Abstract

A relatively simple method is proposed for prediction of residual welding stresses and deformations, originally developed by Okerblom. The main formulae for the shrinkage and curvature of a beam due to one or more single- or multipass welds are derived and applied for prediction of the correct welding sequence in the case of an asymmetric I-section beam with two longitudinal welds. The efficiency of welding in a clamping device without and with prebending is shown in the case of an asymmetric I-section beam with one eccentric longitudinal weld. Numerical examples illustrate the use of derived formulae.

Keywords

Residual welding stresses, residual curvature, welding sequence, welding in clamping device, asymmetric welded I-beams

1. Beam deformations due to a stationary thermal load

Our aim is to give engineers relatively simple formulae for prediction of beam deformations due to weld shrinkage. For this purpose we adopted the Okerblom's method [1,2,3,4].

We assume the following:

- the coefficient of thermal expansion and the Young modulus are independent from the temperature,
- the deflections are in the elastic range, the Hooke-law is valid,
- the cross sections of the beam will be planar after deflection,
- the cross section is uniform,
- the beam is made of one material grade,
- the thermal distribution is uniform along the length of the beam and steady state.

The thermal distribution is nonlinear as shown in Fig. 1. The thermal strain would be different at different points of cross section if they were independent form each other: $\varepsilon = \alpha_o T_e(y)$. Because they are connected to each other, we assume that the cross section remains planar, only a linear strain can occur in the cross section. This linear strain is characterized by the strain of the gravity centre and the curvature of the beam: $\varepsilon = \varepsilon_G + Cy$. The differences between the theoretical thermal strain and the linear strain cause the stresses:

$$\sigma = E\varepsilon = E\{\varepsilon_G + Cy - \alpha_o T_e(y)\} \tag{1}$$

There is no external loading on the beam, so the internal stresses caused by thermal difference are in equilibrium,

$$\int_A \sigma dA = 0 \qquad \text{and} \qquad \int_A \sigma y dA = 0 \tag{2}$$

By inserting Eq. (1) to (2), we get

$$\varepsilon_G = \frac{1}{A}\int_{e_1}^{e_2} \alpha_o T_e(y) t(y) dy \qquad \text{and} \qquad C = \frac{1}{I_x}\int_{e_1}^{e_2} \alpha_o T_e(y) y t(y) dy . \tag{3}$$

If the thickness is constant, i.e. $t(y)=t$ we can define the thermal shrinkage impulse A_T as

$$A_T = \int_{e_1}^{e_2} \alpha_o T_e(y) dy \tag{4}$$

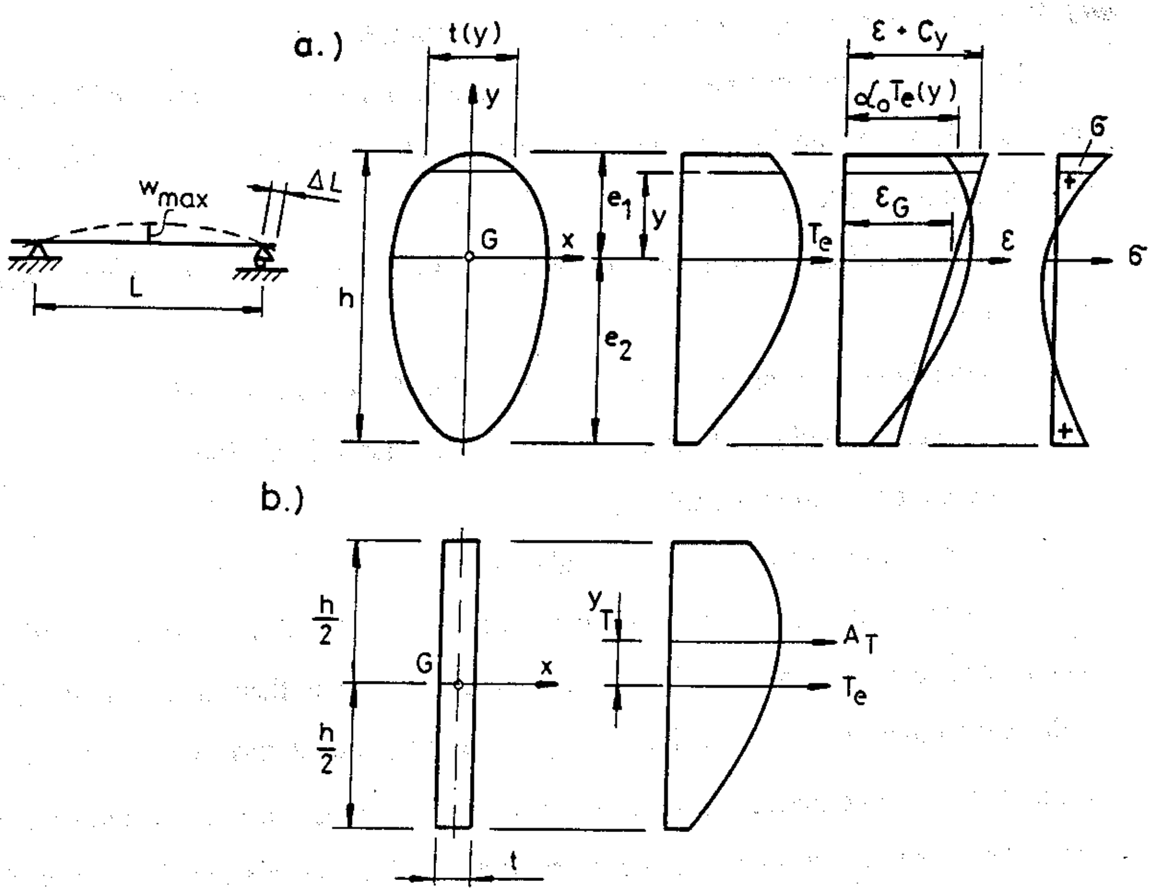

Fig. 1. Beam with nonlinear temperature distribution

The thermal impulsive moment is defined as follows

$$A_T y_T = \int_{e_1}^{e_2} \alpha_o T_e(y) y dy \tag{5}$$

Using these definitions the strain at the center of gravity and the curvature are as follows

$$\varepsilon_G = \frac{A_T t}{A} \tag{6}$$

$$C = \frac{A_T t\, y_T}{I_x} \tag{7}$$

2. Residual beam stresses and deformations due to a longitudinal single-pass weld

When a structural section is welded, it undergoes distortion as a result of thermal shrinkage along the axis of the weld. For example, an edge-welded bar section shortens (ΔL) and

deflects (w_{max}). Experiments indicate that the Okerblom's analysis provides excellent prediction for longitudinal deflections caused by thermal shrinkage along the weld [1,2].
The analytical heat-transfer theory of welding was developed by Rykalin [5]. Okerblom utilised the analytical heat-transfer theory of moving heat sources to establish the thermal strain and stress distributions around the weld. The objective of the Okerblom's analysis is to predict the beam shrinkage (ΔL) and deflection (w) as shown in Fig. 1. Investigate the effect of a longitudinal weld welded on the fiber A (Fig. 2) of an elastic I-beam. The heat impulse causes an elastic strain at the point A ε_A.

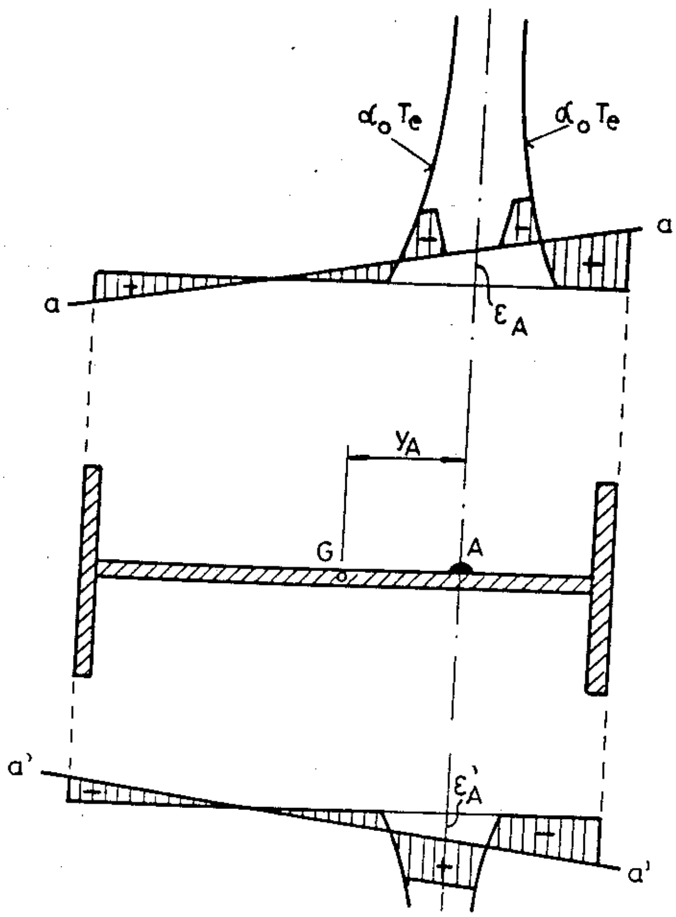

Fig. 2 Strain distribution during and after welding of a longitudinal weld on an elastic I-beam

In the Okerblom's analysis the material is linearly elastic and ideally plastic. The yield stress is constant till 500 C°, and between 500 and 600 C° it decreases to zero. If the temperature is larger than 600 C°, there is no measurable stress in material (Fig. 3).

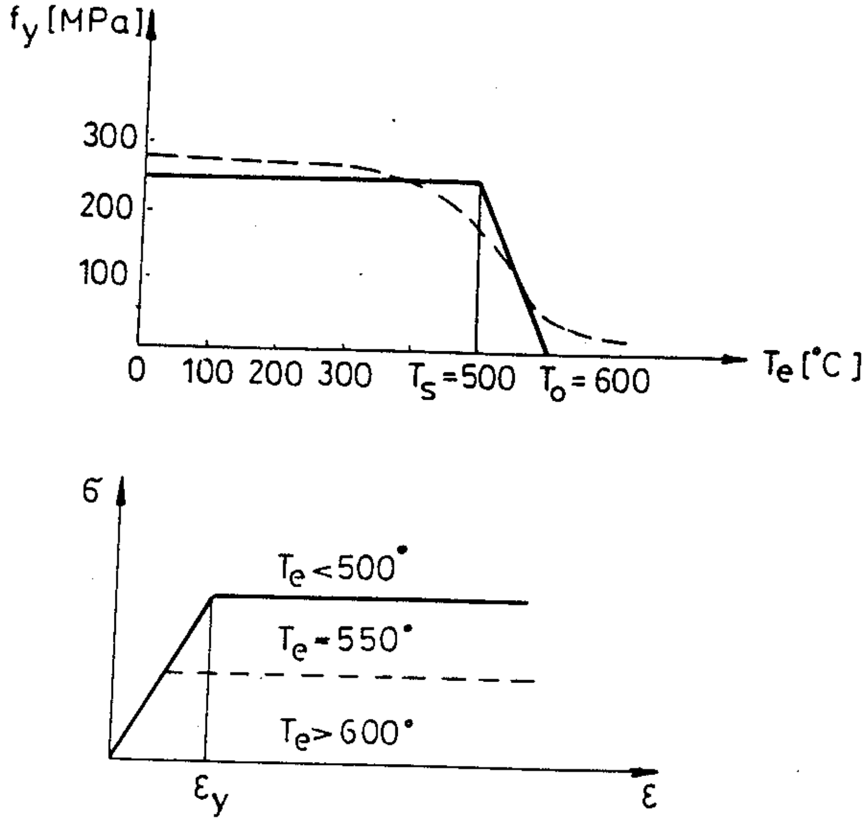

Fig. 3 The yield stress in the function of the temperature and strain

The approximation of the T_e temperature suggested by Okerblom is as follows

$$T_e = \frac{0.4840 Q_T}{c_o \rho t 2y} \tag{8}$$

where c_0 is the specific heat, ρ is the material density, t is the thickness of the plate.

The thermal impulse can be calculated according to Fig. 4, which shows the detail of the I-beam in Fig.2. The diagram determined by points 1-10 shows the stress distribution during welding. It can be obtained by projection of points B and C to the line ε_A which occurs due to elastic deformation of the structure during welding. Points B and C are determined by the line 600° α_o, so between points 5 and 6 no stresses occur. Points 3-4 and 7-8 are obtained by the line parallel to line ε_A in a distance ε_y, with projection to this line the points D and E determined by the line 500° α_o. It can be seen that plastic strains occur during welding between points 3 and 8. These retrained strains cause residual stresses after cooling.

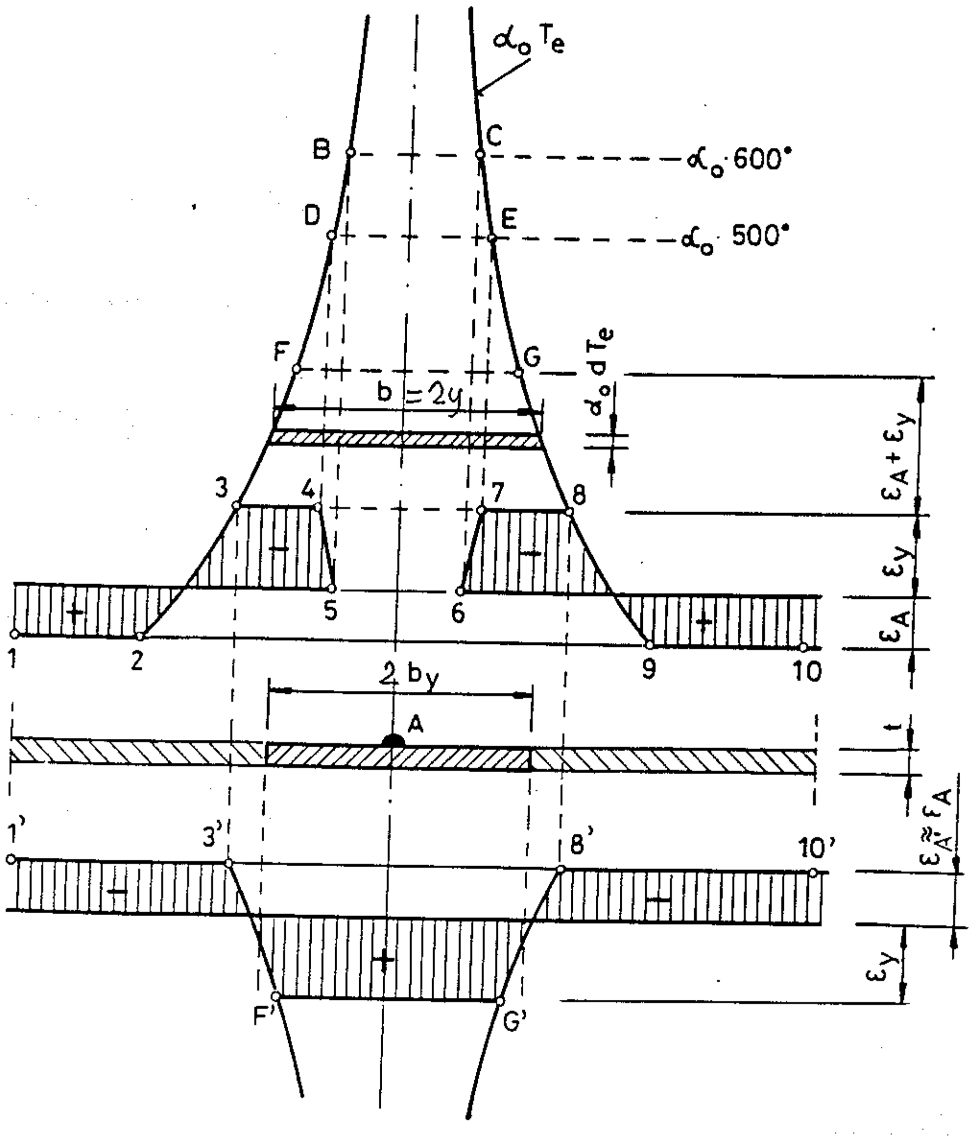

Fig. 4 Distribution of thermal strains during and after welding

The residual stress diagram after cooling can be obtained projecting points 3 and 8 onto the basic line 1'-10'. Considering the elastic deformation $\varepsilon'_A \approx \varepsilon_A$ during cooling and the line of ε_y, one obtains the residual stress diagram 1'-3'-F'-G'-8'-10'. The area 3'-F'-G'-8' characterizes the thermal shrinkage impulse A_T which causes the residual stresses and deformations in the structure.

Since the line parts of 3'-F' and 8'-G' are the same as parts 3-F and 8-G, the A_T can be calculated by investigating the area 3-F-G-8 in the diagram drawn for the state during welding.

$$A_T = \int_{\varepsilon_A+\varepsilon_y}^{2(\varepsilon_A+\varepsilon_y)} b\alpha_o dT_e = \frac{0.4840\alpha_o Q_T}{c_o \rho t} \int_{T_{e1}=(\varepsilon_A+\varepsilon_y)/\alpha_o}^{T_{e2}=2T_{e1}} \frac{dT_e}{T_e} \tag{9}$$

$$A_T = \frac{0.4840\alpha_o Q_T}{c_o \rho t} \ln 2 = \frac{0.3355\alpha_o Q_T}{c_o \rho t} \tag{10}$$

where $Q_T = \eta_o \frac{UI}{v_w} = q_o A_w$, U arc voltage, I arc current, v_w speed of welding, c_o specific heat, η_o coefficient of efficiency, q_0 is the specific heat for the unit cross-sectional area of a weld (1 mm^2), A_w is the cross-sectional area of a weld.

For a mild or low alloy steels, where α_o=12*10^{-6} [1/C°], $c_o\rho$= 4.77*10^{-3} [J/mm^3/C°], the thermal impulse is

$$A_T t \ [\mathrm{mm}^2] = 0.844 * 10^{-3} Q_T \ [\mathrm{J/mm}]$$

For butt welds Q_T(J/mm)=60.7A_w (mm^2), for hand welded fillet welds Q_T=78.8a_w^2 , for a fillet weld in the case of semiautomatic or automatic welding Q_T=59.5a_w^2, where a_w is the fillet weld dimension.

Inserting this into Eqs. (6) and (7), we get the basic Okerblom formulae

$$\varepsilon_G = \frac{A_T t}{A} = -0.844 * 10^{-3} \frac{Q_T}{A} \tag{11}$$

The minus sign means shrinkage.

$$C = \frac{A_T t y_T}{I_x} = -0.844 * 10^{-3} \frac{Q_T y_T}{I_x} \tag{12}$$

Note that the distorted form can be determined by view. y_T and C have opposite signs (Fig. 15).

The elastic strain in the weld can be calculated using the previous two expressions

$$\varepsilon_A = \varepsilon_G + Cy_T \tag{13}$$

The average width of the plastic tension zone around the weld is

$$2b_y = \frac{A_T}{\varepsilon_A + \varepsilon_y} \tag{14}$$

At the region of weld the residual tensile stress after welding reaches the yield stress (Fig. 4). The area of the plastic zone is

$$A_y = 2b_y t = \frac{A_T t}{\varepsilon_A + \varepsilon_y} \tag{15}$$

By using Eqs. (6), (7) and (13) one obtains

$$\frac{1}{A_y} = \frac{1}{A} + \frac{y_T^2}{I_x} + \frac{\varepsilon_y}{A_T t} \tag{16}$$

If no crookedness is developed in beam during welding, as for example in the case of a symmetrical weld arrangement, Eq. (16) takes the form

$$\frac{1}{A_y} = \frac{1}{A} + \frac{\varepsilon_y}{A_T t} \tag{17}$$

For steels

$$\frac{1}{A_y} = \frac{1}{A} + \frac{y_T^2}{I_x} + \frac{14.3}{Q_T} \quad \text{[J, mm]} \tag{18}$$

If the structure can be regarded as a very stiff one, when $\varepsilon_A = 0$, area of plastic zone is

$$\frac{1}{A_y} = \frac{\varepsilon_y}{A_T t} \tag{19}$$

For steels

$$A_y = \frac{Q_T}{1.43} \tag{20}$$

The equilibrium equation for a section with tension and compression stresses is according to Fig. 5

$$(b - 2b_y)\sigma_c = 2b_y f_y \tag{21}$$

Using Eq. (17) one can compute the residual compressive stress,

$$\sigma_c = \frac{A_T\, t f_y}{A\varepsilon_y} = \frac{A_T t}{A} E = \frac{0.3355\alpha_o \eta_o UIE}{c_o \rho v_w\, b\, t} \tag{22}$$

With data $\alpha_o = 11*10^{-6}$, $c_o\rho = 3.53*10^{-3}\left[\frac{\mathrm{J}}{\mathrm{mm^3C^o}}\right]$, $E = 2.05*10^5$ [MPa], v_w is the welding speed, used by White [6,7,8], the Okerblom formula is

$$\sigma_c = \frac{0.214\eta_o UI}{v_w bt}, \tag{23}$$

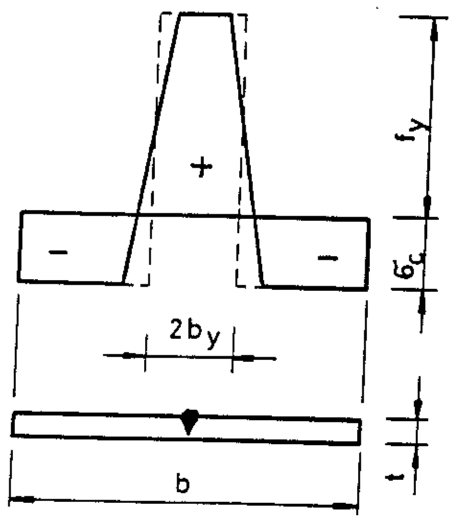

Fig. 5 Approximate stress distribution for a plate with a single weld at the middle

White [6,7,8] proposed an approximate formula based on own experiments

$$\sigma_c = \frac{0.2\eta_o UI}{v_w bt}, \tag{24}$$

It can be seen that Okerblom's formula is in agreement with White's experimental results. The formulae above are valid for symmetrically arranged welds $y_A = 0$ when

$$\frac{Q_T}{A} \le 2.50 \left[\frac{\mathrm{J}}{\mathrm{mm^3}}\right], \tag{25}$$

for eccentric welds $(y_A \neq 0)$ when

$$\frac{Q_T}{A} \le 0.63 \left[\frac{\mathrm{J}}{\mathrm{mm^3}}\right]. \tag{26}$$

For approximate calculations one can use the simple formula

$$\varepsilon_y = \frac{f_y}{E} \tag{27}$$

where f_y is the yield stress of the parent material. The weld metal may have a different yield stress. This discrepancy arises due to the electrode material. In this case it is important to measure the yield stress of the weld metal. Using high strength steels, the yield stress of the weld metal can be smaller that of the parent material. Therefore the residual stresses are relatively smaller, than in the case of mild steel.

The basic Okerblom formulae are valid for single pass-welding. For multi-pass welding it is necessary to modify Eq. (10.), because the new weld pass resolves the plastic zone, made by the previous weld pass. For the value of residual stresses that weld pass is governing, which causes the largest plastic zone. Introducing a parameter for the correction of thermal shrinkage impulse

$$A_T = m_t \frac{0.3355\alpha_o Q_T}{c_o \rho t} \tag{28}$$

where $m_t = \dfrac{A_{yt}}{A_{y1}}$, (29)

A_{yl} , A_{yt} the areas of plastic zone due to single- and multi-pass welding.

For example at a two-pass (equal passes) butt joint $m_t = 1$. For a double fillet weld for thin plates, where the welds are welded one after the other $m_t = 1.2 - 1.3$.

White [6,7,8] suggested to calculate the tendon force from the parameters of that pass, which has the greatest section area.

The effect of preheating can be taken account with a correction parameter

$$F' = (1.1 - \frac{T_p}{1000})F, \quad F = \sigma_c bt \tag{30}$$

where the temperature of preheat is $T_p > 100$ C°.

3. Effect of initial strains

In the previous calculations it was assumed, that there are no initial strains and stresses in the structure. In practice there are usually some strains and stresses before welding, or previous welds cause initial strains and stresses for the next weld(s). Preheating, flame cutting and pre-stressing have the same effect.

The strain diagram is similar to Fig.4 except of the initial tensile strain ε_I. Fig. 6 shows the strain distribution during welding and after welding. The final deformations after welding are caused by the difference of $\varepsilon_y - \varepsilon_I$. The effective zone is between ABCD point. The thermal impulse can be computed as follows:

$$A_T' = \int_{\varepsilon_I+\varepsilon_y}^{2\varepsilon_y} b\alpha_o dT_e = \frac{0.4840\alpha_o Q_T}{c_o\rho t}\int_{T_{e1}=(\varepsilon_I+\varepsilon_y)/\alpha_o}^{T_{e2}=2\varepsilon_y/\alpha_0} \frac{dT_e}{T_e} \tag{31}$$

$$A_T' = \frac{0.4840\alpha_o Q_T}{c_o\rho t}\ln\frac{2\varepsilon_y}{\varepsilon_y+\varepsilon_I} \tag{32}$$

To consider the effect of initial deformation we introduce a modifying parameter ν_m, which is the ratio of the thermal impulse with and without initial strain.

$$\nu_m = \frac{A_T'}{A_T} = 1 - \frac{\ln(1+\frac{\varepsilon_I}{\varepsilon_y})}{\ln 2} \approx 1 - \frac{\varepsilon_I}{\varepsilon_y} \tag{33}$$

The approximate formula is valid when $\frac{\varepsilon_I}{\varepsilon_y} \geq 0$.

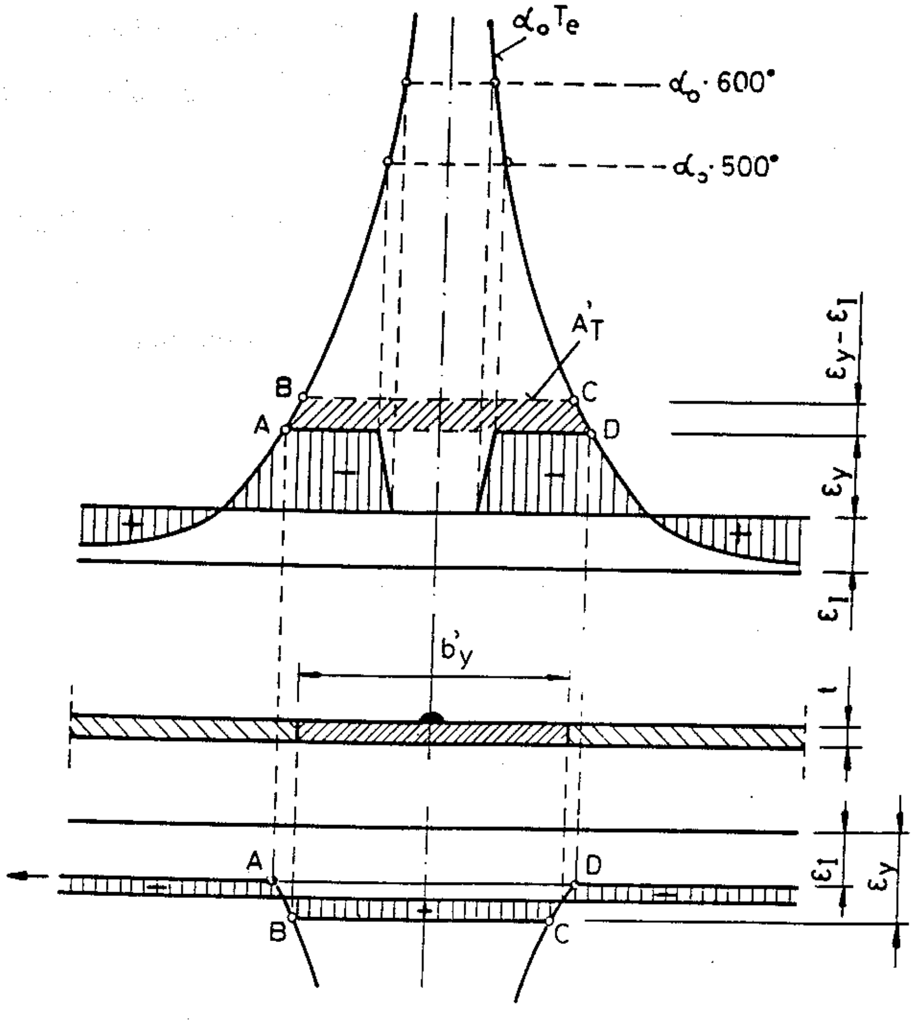

Fig. 6 Distribution of thermal strains during and after welding with initial strains

Fig.7 shows ν_m in the function of $\frac{\varepsilon_I}{\varepsilon_y}$. Without initial deformation no modification is necessary, so if $\varepsilon_I = 0$, then $\nu_m = 1$. If there is a tension in the elastic zone, $0 < \varepsilon_I < \varepsilon_y$, then $1 > \nu_m > 0$. If the initial strain is equal to the yield strain, $\varepsilon_I = \varepsilon_y$, $\nu_m = 0$, there is no residual stresses and deformations after welding. If the initial strain is negative (compression), $\varepsilon_I < 0$, $\nu_m > 1$, this strain increases the deformation, but the approximate formula cannot be used.

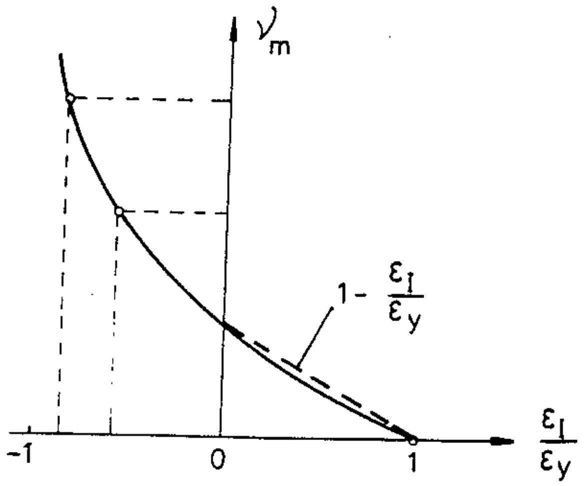

Fig.7 Modifying parameter in the function of initial strain

The thermal shrinkage impulse is according to Fig.6

$$A_T' = \frac{b_y'}{\varepsilon_y - \varepsilon_I} \tag{34}$$

the area of plastic zone is

$$A_y' = b_y' t = \frac{A_T' t}{\varepsilon_y - \varepsilon_I} = \frac{\nu_m A_T t}{\varepsilon_y - \varepsilon_I} \tag{35}$$

if $\varepsilon_i > 0$ then $A_y' = \frac{A_T t}{\varepsilon_y}$ and for a normal grade steel $A_y' = \frac{Q_T}{1.43}$ (J, mm).

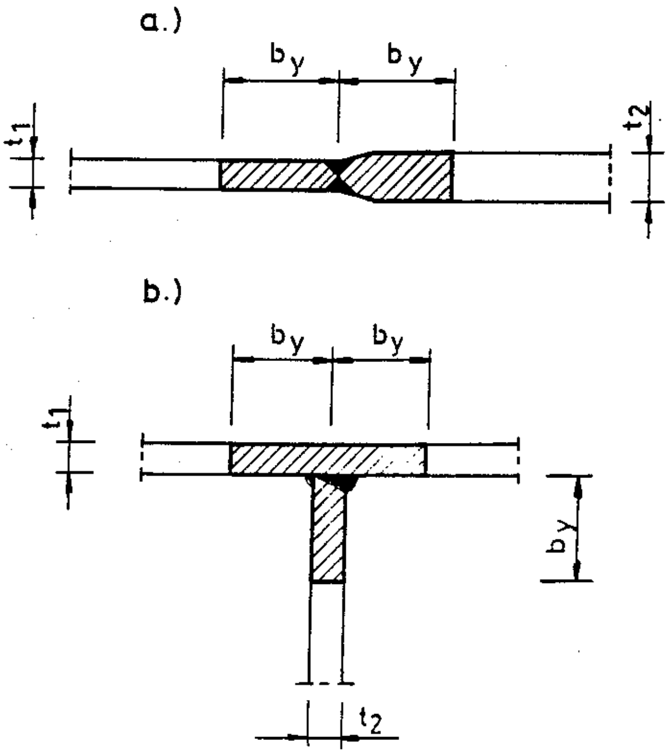

Fig. 8 The area of plastic zone

4. The correct welding sequence of an asymmetric I-section beam with two longitudinal welds

By using the modifying parameter it is possible to deternine the right welding sequence. If there are more welds on a structure, the welding sequence can be very important, its effect on the final strain is significant. Calculating v_m, one can compute the effect of the welds on each other, how large is the initial deformation at the place of the other weld, what is this effect on the total deformation, what is the effect of changing the welding sequence (Fig.9).

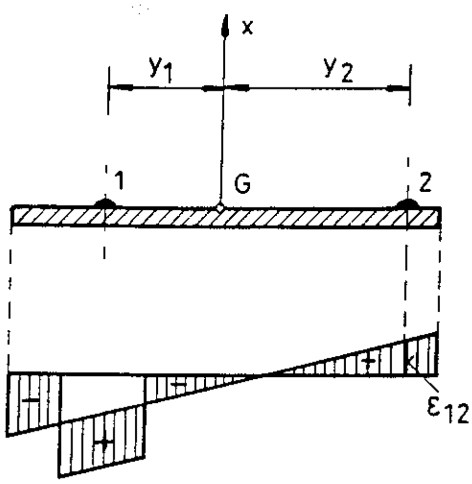

Fig. 9 Initial strain in the place of the second weld due to the first weld

The strain at the gravity centre line and the curvature are as follows

$$\varepsilon_{G1} = \frac{A_{T1}t}{A}; \qquad C_1 = \frac{A_{T1}ty_T}{I_x}, \tag{36}$$

$$\varepsilon_{I12} = \varepsilon_{G1} + C_1 y_2 = A_{T1}t\left(\frac{1}{A} + \frac{y_1 y_2}{I_x}\right), \tag{37}$$

the modifying factor

$$\nu_{m12} = 1 - \frac{\ln(1 + \frac{\varepsilon_{I12}}{\varepsilon_y})}{\ln 2} \approx 1 - \frac{\varepsilon_{I12}}{\varepsilon_y} \tag{38}$$

expresses the effect of the first weld at the place of the second weld.

The final strain and curvature caused by two welds is

$$\varepsilon_{G(1+2)} = \varepsilon_{G1} + \nu_{m12}\varepsilon_{G2} = \varepsilon_{G1}\left(1 + \nu_{m12}\frac{Q_{T2}}{Q_{T1}}\right), \tag{39}$$

$$C_{1+2} = C_1 + \nu_{m12}C_2 = C_1\left(1 + \nu_{m12}\frac{Q_{T2}y_2}{Q_{T1}y_1}\right). \tag{40}$$

Changing the welding sequence $\varepsilon_{G(2+1)}$ and C_{2+1} can be calculated using Eqs (39) and (40), changing the subscripts:

$$\varepsilon_{G(2+1)} = \varepsilon_{G2} + \nu_{m21}\varepsilon_{G1} = \varepsilon_{G2}\left(1 + \nu_{m21}\frac{Q_{T1}}{Q_{T2}}\right), \tag{41}$$

$$C_{2+1} = C_2 + \nu_{m21}C_1 = C_2\left(1 + \nu_{m21}\frac{Q_{T1}y_1}{Q_{T2}y_2}\right). \tag{42}$$

Comparing the two strains and curvatures, the smallest absolute value gives the better welding sequence.

If there are two longitudinal welds in an asymmetric I-beam and the first weld is closer to the gravity center, $y_1 < |y_2|$, it means $C_1 < |C_2|$, so the second weld has greater effect that the first one. The modifying parameter is always less then 1 in this case, $0 < \nu_m < 1$. The conclusion is that the correct welding sequence is to weld first the weld which is nearer to the gravity center, since the prestressing effect of this weld decreases the larger effect of the weld with larger eccentricity.

5. Welding in a clamping device of an asymmetric I-section beam with one eccentric weld

The production sequence is: tacking, clamping, welding, loosening (Fig.10).
During welding the deformation w occurs, but it is restrained by clamping moments M. The bending moment necessary to keep the beam straight against the welding deformations in

$$M = I_\xi EC \tag{43}$$

where I_ξ is the moment of inertia for the elastic part of the cross-section area, calculated without the plastic zone A_y, C is the curvature of the beam caused be welding in free state.
It is assumed, that the beam material is ideally elasto-plastic, that means that the tensile stress in the plastic zone cannot be larger than the yield stress, so this zone cannot be loaded beyond this limit.

The loosening of the clamped state acts as the bending moments M with opposite sign. These moments cause compressive stresses in the plastic zone which behaves elastically during this unloading, this one can calculate with the moment of inertia of the whole cross-section I_x. Thus, after the loosening of the clamped state the following curvature occurs

$$C' = \frac{M}{EI_x} = C\frac{I_\xi}{I_x} \tag{44}$$

where I_x is the moment of inertia for the total elastic section area.

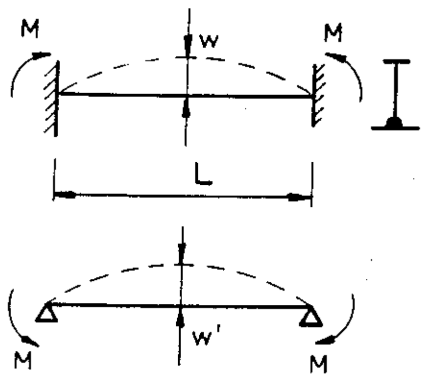

Fig.10 Welding in a clamping device

It can be concluded, that using a clamped state the residual welding deformations cannot be totally eliminated, they can be decreased only in a measure of $\frac{I_\xi}{I_x}$, $C' < C;\ C' \neq 0$. The ratio between the two curvatures depends on the area of the plastic zone.

6. Welding in clamping device with prebending

The production sequence is: tacking, prebending, clamping, welding, loosening (Fig. 11).
To prevent very large deformations and cracks, it is advisable to use prebending moments not larger than

$$M_y = \frac{f_y I_x}{y_{\max}} \tag{45}$$

The curvature and deformation caused by M_y are

$$C_y = \frac{M_y}{EI_x}, \qquad w_y = \varepsilon_y \frac{L^2}{8y_{\max}} \tag{46}$$

The prebending $w_p < w_y$ causes a tensile prestrain in the place of the longitudinal weld

$$\varepsilon_P = C_p y_T = w_p \frac{8y_T}{L^2} \tag{47}$$

the corresponding modifying factor is

$$\nu_m = 1 - \frac{\varepsilon_P}{\varepsilon_y} \tag{48}$$

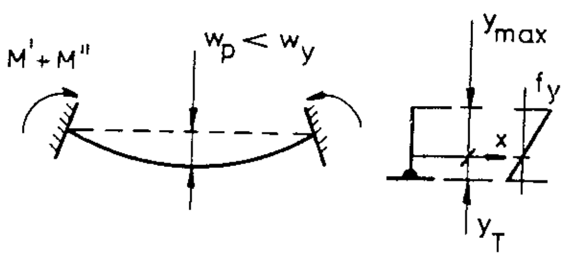

Fig. 11 Welding in prebent state in clamping device

The bending moment necessary to keep straight the beam after welding consists of two parts as follows: the moment which is necessary for prebending

$$M' = I_\xi E C_p = 8 w_P \frac{EI_\xi}{L^2} \tag{49}$$

and the moment which is necessary to eliminate the residual welding deformations

$$M'' = \nu_m I_\xi E C = 8 \nu_m w \frac{EI_\xi}{L^2} \tag{50}$$

These moments act opposite after the loosening and decrease the prebending deformations,

$$M = M' + M'' = I_\xi E C_p + \nu_m I_\xi E C \tag{51}$$

so that the remaining final deformations can be expressed as

$$w_f = w - w_p = \frac{M' + M''}{8EI_x} L^2 - w_p \tag{52}$$

$$w_f = (w_p + \nu_m w)\frac{I_\xi}{I_x} - w_p \tag{53}$$

where $\nu_m = 1 - \frac{8 w_p y_T}{L^2 \varepsilon_y}$

I_x is the moment of inertia for the elastic section area.

I_ξ is the moment of inertia for the elastic section area, reduced by the plastic zone,

C is the curvature of the beam caused be welding in free state,

ν_m is the correction parameter according to Eq. 48.

The prebending w_P necessary to totally eliminate the residual welding deformations can be calculated from the condition $w_f = 0$

$$w_p = \frac{w}{\frac{I_x}{I_\xi} + \frac{8 y_T w}{L^2 \varepsilon_y} - 1}. \tag{54}$$

7. Numerical examples

7.1 Suitable welding sequence in the case of a welded asymmetric I-beam

Find the best welding sequence for two longitudinal welds of an asymmetric I-beam (Fig.12)

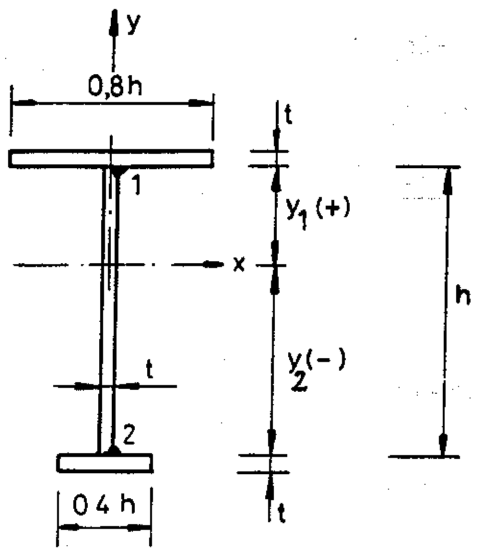

Fig. 12 Welding sequence for an asymmetric I-beam

Section dimensions

t = 10 mm, h = 600 mm, L = 6 m, steel grade Fe 360

Welding parameters

$$Q_{T1} = Q_{T2} = 60.7\,A_{w1} \left[\frac{\text{J}}{\text{mm}}\right], \qquad A_{w1} = A_{w2} = 100 \text{ mm}^2.$$

Determination of the center of gravity

$$0.8ht\left(\frac{h+t}{2} - y_0\right) - hty_0 - 0.4ht\left(\frac{h+t}{2} + y_0\right) = 0,$$

$$y_0 = 55.5 \text{ mm}.$$

Determination of the moment of inertia

$$I_x = \int_{(a)} y^2 dA = \frac{h^3 t}{12} + hty_0 + \frac{0.8ht^3}{12} + 0.8ht\left(\frac{h+t}{2} - y_0\right)^2 + \frac{0.4ht^3}{12} + 0.4ht\left(\frac{h+t}{2} + y_0\right)^2,$$

$$I_x = 8.881*10^{-4} \text{ mm}^4,$$

With Eq.11 $\varepsilon_{G1} = -0.844 * 10^{-3} \dfrac{Q_{T1}}{A} = -3.881 * 10^{-4}$,

$$A = 0.8*600*10 + 600*10 + 0.4*600*10 = 1.32*10^4 \text{ mm}^2,$$

Eq.12: $C_1 = -0.844*10^{-3}\frac{Q_{T1}y_{T1}}{I_x} = -0.844*10^{-3}\frac{60.7*100*244.5}{8.09247*10^8} = -1.548*10^{-6}\ \left[\frac{1}{\text{mm}}\right]$,

$$\varepsilon_{I12} = \varepsilon_{G1} + C_1 y_2 = -3.881*10^{-4} - 1.548*10^{-6}*(-355.5) = 1.6216*10^{-4},$$

the modifying factor is, according to Eq.33

$$v_{m12} = 1 - \frac{\varepsilon_{I12}}{\varepsilon_y} = 1 - \frac{1.6216*10^{-4}}{1.119*10^{-3}} = 0.855$$

$$\varepsilon_{G2} = |\varepsilon_{G1}| = 3.881*10^{-4},$$

$$C_2 = -0.844*10^{-3}\frac{Q_{T2}y_{T2}}{I_x} = -0.844*10^{-3}\frac{60.7*100*(-355.5)}{8.09247*10^8} = 2.251*10^{-6}\ \left[\frac{1}{\text{mm}}\right],$$

The final strain and curvature after the two welds in sequence 1+2 are as follows

$$\varepsilon_{G(1+2)} = \varepsilon_{G1} + v_{m12}\varepsilon_{G2} = -3.881*10^{-4} + 0.855*3.881*10^{-4} = -5.627*10^{-4},$$

$$C_{1+2} = C_1 + v_{m12}C_2 = -1.548*10^{-6} + 0.855*2.251*10^{-6} = 3.77*10^{-7}\ \left[\frac{1}{\text{mm}}\right].$$

For the welding sequence 2+1 one obtains

$$\varepsilon_{I21} = \varepsilon_{G2} + C_2 y_1 = 3.881*10^{-4} + 2.251*10^{-6}*244.5 = 9.3847*10^{-4},$$

the modifying factor is

$$v_{m21} = 1 - \frac{\varepsilon_{I21}}{\varepsilon_y} = 1 - \frac{9.3847*10^{-4}}{1.119*10^{-3}} = 0.1613$$

$$\varepsilon_{G(2+1)} = \varepsilon_{G2} + v_{m21}\varepsilon_{G1} = 3.881*10^{-4} + 0.1613*(-3.881*10^{-4}) = 3.2549*10^{-4},$$

$$C_{2+1} = C_2 + v_{m21}C_1 = 2.21*10^{-6} + 0.1613*(-1.548*10^{-6}) = 2.001*10^{-6}\ \left[\frac{1}{\text{mm}}\right],$$

$$y_1 < y_2;\ C_1 < C_2;\ C_{1+2} < C_{2+1}.$$

Changing the welding parameters to reduce the final deformation to zero.

From $$C_{1+2} = C_1 + v_{m12}C_2 = C_1 + v_{m12}C_1\frac{Q_{T2}y}{Q_{T1}y_1} = C_1\left(1 + v_{m12}\frac{Q_{T2}y}{Q_{T1}y_1}\right) = 0$$

we get $$\frac{Q_{T1}}{Q_{T2}} = -v_{m12}\frac{y_2}{y_1} = -0.855*\frac{-355.5}{244.5} = 1.243$$

so if $Q_{T1} = 6.07*10^3$ and $Q_{T2} = 4.88*10^3$ $\left[\frac{\text{J}}{\text{mm}}\right]$, then the final deformation $C_{1+2} = 0$.

Choosing a good welding parameter ratio one can reduce the deformation of the welded structure.

7.2 Welding in a clamping device

Fig. 13 shows welding of an asymmetric I-section made in free state, in a clamping device and in prebent state.

Data: $Q_T = 950 \left[\frac{\text{J}}{\text{mm}}\right]; L = 7$ m, $E = 2.1*10^5$ MPa, $f_y = 240$ [MPa].

Determination of the gravity center

$$\int_{(A)} ydA = 0; y_T = 26 \text{ mm}, y_0 = 24 \text{ [mm]}.$$

Determination of the moment of inertia

$$I_x = \int_{(A)} y^2 dA; I_x = 1.1381*10^8 \text{ [mm}^4\text{]}.$$

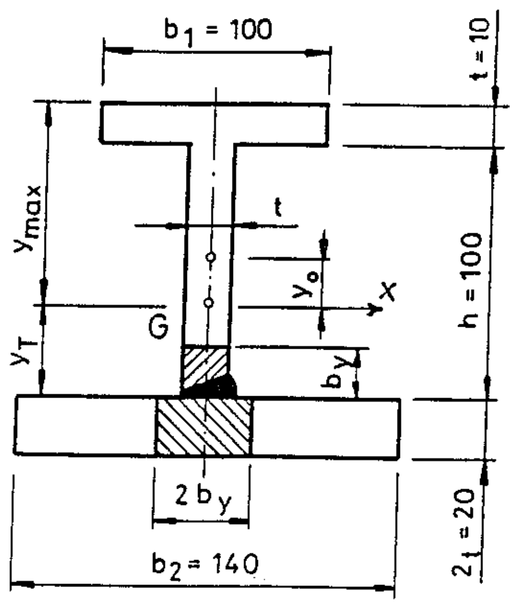

Fig. 13 Welding of an asymmetric I-section made in free state, in clamping device and in prebent state

Welding in free state

$$C = -0.844 * 10^{-3} \frac{Q_T y_T}{I_x} = 1.827 * 10^{-6} \left[\frac{1}{mm}\right], \qquad w = \frac{CL^2}{8} = 11.19 \ [mm].$$

Welding in clamping device, according to Eq.44

$$w' = w \frac{I_\xi}{I_x}.$$

Cross section area and width of the yield zone is

$$A_y = \frac{Q_T}{1.43} = 5b_y t = 664 \ [mm^2], \qquad b_y = 13.3. \ [mm].$$

The moment of inertia decreasing the section with the yield zone is

$$I_\xi = \int_{(A)} y^2 dA = 1.033 * 10^8 \ [mm^4],$$

$$C' = C \frac{I_\xi}{I_x} = 1.658 * 10^{-6} \left[\frac{1}{mm}\right], \qquad w' = C' \frac{L^2}{8},$$

$$w' = w \frac{I_\xi}{I_x} = 10.15 \ [mm].$$

It can be seen that $w' < w$, but $w \neq 0$.

7.3 Welding in prebent state in a clamping device

Consider the same I-section in Fig. 13.

With the data $y_T = 26$ mm; $w = 11.19$ mm; $\varepsilon_y = 1.119 * 10^{-3}$, using Eq.54 we obtain

$$w_P = 77.605 \ \text{mm}.$$

The prebending should be in the elastic zone.

The limit prebending deflection is as follows

$$w_y = C_y \frac{L^2}{8} = \varepsilon_y \frac{L^2}{8 y_{max}} = 83.12 \ \text{mm},$$

where $y_{max} = 84$ mm.

Since the prebending deflection is less than the yield deflection, so the result is suitable.

Conclusions

The simple formulae for prediction of residual welding stresses and deformations, originally developed by Okerblom, have been verified by White's experiments. The method is suitable for prediction of residual stresses and deformations of beams due to one or more single- or multipass longitudinal welds. In the case of an asymmetric I-beam with two welds the correct welding sequence is to weld first the weld which is nearer to the gravity center, since the prestressing effect of this weld decreases the larger effect of the weld with larger eccentricity. The use of a clamping device does not eliminate the whole residual curvature of a beam with one eccentric weld. In order to eliminate totally the residual curvature a prebending is necessary. The derived formula is suitable to calculate the measure of prebending.

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